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Our briefing will cover the:
- F/A-18 Aircraft
- An overview of the Hornet's Flight Control System
- A brief synopsis of selected flight controls system related mishaps.
- Our testing of the software, or "Operational Flight Program" which in a highly augmented, fly-by-wire aircraft constitutes a new flight control system.
- Results and Conclusions
- And a brief overview of lessons learned.

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Flight & Ground Testing of New Flight Control Software for the F/A-18 Hornet

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Good day ladies and gentlemen, my name is Major Loria, and with me today is Mr. Beck.

We were the Project Officer and Project Engineer for the flight test & simulation portions of this test project.

Our goals today are to present the lessons learned from a safety aspect; in regards to the Hornets Flight Control System, the continuing improvement of that system, and the simulation and flight test of new flight controls laws.

Flight & Ground Testing of New Flight Control Software for the F/A-18 Hornet

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TOPICS OF DISCUSSION

- The F/A-18 Hornet
- Flight Control System Design & Operation
- Operational & Mishaps Lessons Learned
- Operational Flight Program Testing
  - Lab, Simulator & Ground Testing
  - Flight Testing
- Results & Conclusions
- Lessons Learned

Our briefing today will cover the:

F/A-18 Aircraft

An overview of the Hornet's Flight Control System

A brief synopsis of selected flight controls system related mishaps.

Our testing of the software, or "Operational Flight Program" which in a highly augmented, fly-by-wire aircraft constitutes a new flight control system.

Results and Conclusions.

And a brief overview of lessons learned.

THE F/A-18 HORNET

- Flight Controls System
  - Four Channel, Fly-by-Wire Flight Control System
  - Two Hydraulic systems; four total circuits
  - Control Surface actuators feature multiple levels of electrical & hydraulic redundancy
- Care-free handling qualities:
  - Aircrew can concentrate on employing their weapons & defeating the enemy

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The F/A-18 Hornet enjoys care-free handling qualities throughout the flight envelope.

The system has been designed with reliability, & maintainability, ~~&~~ as primary goals. The life blood of the flight controls is the aircraft's two hydraulic systems, which are independent and driven mechanically by the aircraft engines. Furthermore, the two systems are further divided into two hydraulic circuits for further redundancy.

The ailerons, rudders, and leading edge flaps feature dual redundancy electronically, with simplex hydraulic, but with a hydraulic switching valve for a backup hydraulic source. The trailing edge flaps and stabilators are quad redundant electrically (dual fail op). The trailing edge flaps have dual redundant hydraulics, and the stab goes an extra measure, they have dual redundant hydraulics with a switching valve to back-up one hydraulic source (e.g. dual hyd redundancy w/ a third hyd source via a switching valve).

The bottom line is that Hornet Aircrew enjoy unparalleled flying qualities which enables them to devote their concentration on employing the aircraft tactically.

HORNET FLIGHT CONTROLS

- Reliability, Maintainability & Dependability
  - Faired-Flutter Damped Mode:
    - » Ailerons
    - » Rudders
  - Stabilators
    - » Mechanical Back-up Mode
    - » Bypass Mode & Streamline:
  - Lock- in-Position:
    - » Leading Edge Flaps (Lock at failed position)
    - » Trailing Edge Flaps (Moves to zero deg and locks)

The flight controls system has been designed for reliability, maintainability and dependability. The aircraft enjoys mission capable rates unmatched by any other fixed wing asset in the US inventory.

The aircraft was designed the Strike Fighter mission with resistance to battle damage, and maximum get home capability also key design drivers.

The fail to faired-flutter damped mode was designed into the ailerons, and rudders. The stabilators having quad electronic, triplex hydraulic with Mechanical Mode, and back-up are extremely dependable and reliable. These flight control surface reversionary modes have however, never been flight tested.

The leading edge flaps, by virtue of their location and range of motion have integral brakes on the leading edge flaps transmission which will lock a leading edge flap in position should it fail to follow normal scheduling.

Trailing edge flaps having dual hydraulic and quad electrical redundancy are again quite reliable. However, in the event they, or one should fail, the control surface will *move to zero degrees (by hydraulic power or airloads) and* lock in place to minimize a split flap condition.

Operational Lessons Learned

- Good, well thought out system, with respect to the expected threat to aircraft & aircrew.
- Few battle damaged flight controls to date
- REAL THREAT has so far turned out to be failures encountered during training and the takeoff and landing phases.

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Basically we have a very good, dependable system that has served, and continues to serve remarkably well for the planned threats.

For the purposes of this briefing, and to cover the high points of the flight controls software upgrades, we will review a few selected items, or areas.

Certain recent mishaps have demonstrated the significant threat to aircrew and aircraft posed by complete loss of a single Angle of Attack probe input to the flight controls system and certain control surface actuator failures.

The tragic fact about the Angle of Attack and actuator failures is that when they occur close to the ground, as in the takeoff and landing phases; there is precious little time to react to the resulting transients that may rapidly place the pilot out of the ejection envelope.

Hornet Flight Control System

- Longitudinal Outer Loop Feedback:

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Here is a simplified diagram of the Hornet's longitudinal axis control architecture.

As seen by the location of the Angle of Attack feedback, it becomes patently obvious that this is a major input to the longitudinal axis, pitch control and stabilator commanded position.

Although the AOA probes have quadruplex interfaces with the flight control computers (two position transducers per probe), the probes are only dual redundant with respect to mechanical failures like a jammed probe.

In cases where the dual redundant Angle of Attack Probes have a single AOA Probe failed at an extreme of its travel, an unrecoverable pitch transient results under prior flight control software architecture.

Last year we unfortunately lost an F/A-18 and young Naval Aviator off a catapult launch from a carrier, at sea due to such a failure.

Hornet Flight Control System

- Lateral-Directional Outer Loop Feedback:

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In this simplified control law architecture diagram of the lateral-directional axis, things are more difficult to break out and see the effects of.

First, as with most aircraft, lowering the landing gear, and flaps has a net destabilizing effect on the aircraft's directional stability. The directional stability margin in the all configurations and phases of flight is normally more than adequate. In the takeoff and landing phases, *angle-of-attack is limited to 15 degrees or less by the flight manual.*

Above this value, the directional stability decreases rapidly, and the dihedral effect remains strong, so that any sideslip results in a significant rolling moment that can rapidly exceed the remaining roll control power.

In situations where the rudder has failed during the takeoff and landing phases, aircrew have sometimes unfortunately allowed angle of attack to increase while attempting to reduce the induced roll due to sideslip. *When a rudder fails under prior Hornet flight control laws, any toe-in or out on the "good" rudder is removed at a rapid rate, and then follows normal rudder commands. In the takeoff and landing phases, the rate of removal of rudder toe-in on the "good" rudder was much faster than the blow-back rate of the failed rudder.*

With half of the normal rudder control power removed, and angle of attack and sideslip angle increasing, a departure follows quickly.

Hornet Mishap Simulation Video

- Video from simulation:
  - F/A-18C
  - 2 Wing tanks, 4 Mk-83's, 2 CATM -7's, 2 CATM-9's & 578 Rounds of 20mm
  - 49,000 lb. Gross Weight Aircraft
  - One Angle of Attack Probe failed at 54 degrees
  - Steam Catapult #2, "generic" Aircraft Carrier

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The following video is from simulation conducted at the Manned Flight Simulator facility at the Naval Aircraft Weapons Center, Aircraft Division, Patuxent River.

The aircraft simulated was a F/A-18C, with two wing tanks, four Mark-83 1,000 lb bombs, two captive carry Aim-7 Sparrows and two captive carry Aim-9 Sidewinder missiles. In the video, the aircraft you will see will visually lack this configuration due to limitations of the visual presentation. However, the simulator accurately models the incremental store weights, contributions to center of gravity and effects on aircraft performance and handling qualities.

During the catapult stroke the left angle of attack probe fails at the extreme positive value. This occurs prior to AOA feedback, and the flight controls system, once airborne recognizes the mismatch in AOA and uses the "last best known value" assumed to be from prior to weight off wheels. The tragic fault in this basic assumption is that the AOA probe has failed prior to weight off wheels.

For most instances of this failure, the resulting pitch transient is unrecoverable.

Hornet Mishap Simulation Video

- Video from simulation:
  - F/A-18C
  - Centerline fuel tank, 2 Mk-83's on the Right Wing, 2 CATM -7's, 2 CATM-9's & 578 Rounds of 20mm
  - 44,000 lb. Gross Weight Aircraft
  - Left Rudder Actuator Fails during Catapult
  - Steam Catapult #2, "generic" Aircraft Carrier

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Again this simulation was conducted at Pax River.

The external stores load-out has been changed. This configuration was selected due to actual incidents, and because it exacerbates this particular failure.

During the catapult stroke the left rudder fails *starting* its toed in position of 30 degrees. In the Hornet, the rudders are "toed-in" during takeoffs to optimize pitch rate and fly-away angle of attack capture. The failure of a rudder actuator will be detected, and once weight is off the main wheels, the toe-in command is removed (due to the failure), which results in poorer rotation, and asymmetric rudder position *as toe-in on the remaining* good rudder is *removed.*

The resulting yaw and roll due to the failed rudder position is controllable, only if the angle of attack and sideslip are kept to a minimum. Otherwise significant transients can occur which can rapidly place the pilot out of the survivable ejection envelope.

Flight Controls System Update

- Initiated as a "Must fix now" priority
- Common Flight Controls System software for all Hornets,
  - F/A-18A-D, US and Foreign Military Sales
    - » Less Risk
    - » Fewer Costs
    - » Improves Safety
- "Low Budget, Minimum Risk,...no changes to basic aircraft modes or flying qualities."

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Unfortunately, the flight controls system, its hardware and software architecture do not undergo **scheduled** continual refinement or improvement throughout the life of the airframe. Typically many flight controls system improvements, both performance and safety related can be low enough priority to not be implemented until such time as they rise markedly in the priority rankings.

In response to significant safety issues, it is possible to update the flight controls. The preferable methodology would be to entertain these improvements, and incorporate "beta" or flight test versions only that can undergo planned improvement, and evaluation.

In light of the real world constraints of finite budgets, and multiple priorities we are thankful for this recent series of flight controls system upgrades. The basic gameplan going into this evolution was to incorporate **only** those **required** safety improvements, while minimizing costs and risks.

The requirements were successful implementation of the safety improvements, with no impact to normal, or current operating modes, flying qualities or performance.

GROUND TESTING

- Simulator Preparation - Implementing the FCS Software Change
  - FORTRAN: Small Stuff Counts - BIG!
    - » Coding From The Proper System Documentation
    - » Human error in resulted in the Simulator being not representative of the real Aircraft/Flight Control system, e.g. no ramp in gain changes or alpha or beta values
- Regression Testing

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Prior to receiving the actual upgrade to the flight controls software we had received substantial documentation of the changes, decision matrices and code.

To minimize the fleet's exposure to operational risks that this upgrade was to fix, we began to write a ground test "*quick-look*" copy of the new software load. This was done in FORTRAN, by following the system descriptions and documentation.

One area of difficulty was in learning and writing into the code all the changes that would be present in the new software. As we found out, some of the system descriptions and flow charts were simplified or abbreviated versions. Of course, this meant that our early bird efforts were meant well, but improperly done. Accordingly many man-hours were lost.

A classic case of engineers and technicians working closely with aircraft and systems, but missing a basic detail also ensued. After the correct hardware and contract supplied software was incorporated in lab, during regression and simulator testing we uncovered another gotcha'. Certain failure modes, and flight operations involved values of angle of attack and beta that changed with time. Unfortunately, this was overlooked, and step changes in AOA and Beta were written into the simulator operating software which accordingly resulted in flying qualities anomalies, or anomalies that were significantly magnified by this mistake. In due course these errors were also found and corrected. This highlights the requirement for close aircrew/engineer interaction and exchange of information, during testing, and also applies during requirements development.

Additionally regression testing was satisfactorily conducted to evaluate reversionary modes and logic that could not be flight tested.

GROUND TESTING

- Hardware in The Loop Simulation is **<u>VITAL</u>**.
- Piloted Simulation
  - "No changes to basic a/c modes or flying qualities."
  - "Spot Check" mentality vs. BIG PICTURE
  - Scenarios must be to a logical conclusion

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From the ground based testing we had come to a significant conclusion upon which we based all subsequent ground testing. That <u>hardware in the loop</u> and <u>actual software</u> were <u>REQUIRED</u> to conduct the actual tests.

For the piloted simulation, a wide variety of Navy and Marine pilots were used. Numerous simulations were conducted using different scenarios. Also pilot types were varied from low gain to high gain and then to worst case - or aggravated inputs.

Based on the briefed premise and objective of "no changes to basic aircraft flying qualities or modes" and urge to complete testing and get the life saving improvements to the fleet; we were not expecting anything untold or abnormal. Also, prior flight controls software upgrades had been a ho-hum evolution. Accordingly, some individuals approached this testing with a spot check only mentality.

This soon proved an unwise outlook as we uncovered severe anomalies in the dual probe angle of attack logic. This was a well meant no-cost attempt by contractor to provide fail-safe operation for a dual AOA probe failure. The software changes for dual AOA probe failures would be life saving, if off the catapult the flaps were raised during the ten seconds the software provided fixed AOA gains to the flight control computers. After that the software reverted to the erroneous last best known value and unrecoverable nose-down pitch transients resulted. This proved to be a futile effort to correct for a statistically extremely unlikely dual AOA probe failure. Also this again highlighted the shortcomings of an electrically quad redundant flight controls system, that has duplex AOA hardware, when triplex or quad redundant would be more appropriate given the longitudinal axis dependency of AOA feedback.

For the single AOA probe failures, for certain values of AOA failure severe pitch transients would occur as the software cycled through logic and in and out of fixed AOA values. This was not evident until we insisted that the inserted failures be flown to a safe recovery, field or carrier.

GROUND TESTING

- Piloted Simulation (continued)
  - Good data quantity, poor coverage of envelope - takeoff and landing phases.
  - Programmatics must not interfere with solid test & evaluation - from within the test team or without!
  - Do Deficiencies Exist?

    Then state it!

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A significant learning point was to ensure that not just were carrier evolutions or failures simulated. Granted that carrier operations pose unique performance demands upon the pilot and aircraft and are even more unforgiving than land based operations.

The Hornet is flown differently by units within the Navy and Marine Corps, and then again by other nations flying this great aircraft. The scope of the simulation was expanded to include all flight manual approved takeoff and landing techniques, with normal, low, high gain and aggravated inputs. Additionally the Navy Flight Demonstration Squadron the Blue Angles operate uniquely, executing filed takeoffs with only flaps retracted and no stabilator trim. Finally we had to fly the extremes of the envelope with respect to gross weights, cg's, and lateral asymmetries for all types of takeoffs and recoveries.

The deficiencies that were stated before regarding the dual AOA probe failure detection logic and cycling pitch transients due to software were downplayed by some. The belief was that these deficiencies were acceptable in light of the overall improvements resident in the system upgrade, and that we did not want to "kill" the program. We had a time reminding a few test team members that as testers we do not kill anything, but merely report our findings and conclusion and recommendations.

In the end of this ground phase, the systems shortcomings were appropriately documented and we proceeded to flight test.

Flight Testing

- Normal modes of operation and Mission Tasks are primarily evaluated by qualitative pilot comments and evaluation.

  (CH HQR & PIO Scale)
- Envelope Verification
  - Classic FQ&P, Pilot Relief Modes, Mission Tasks
- Inflight Simulation of Failures - PSFCC's

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For the flight test portion, the normal flight controls operation was documented by standard performance and flying qualities testing.

Qualitative pilot comments on handling qualities were vitally important, especially during the mission tasks portion of the testing. Such testing is highly subjective and requires, as always careful planning and the designing of appropriate tasks, with corresponding adequate and desired criteria.

Currently the Navy and NASA are preparing to flight test Production Support Flight Control Computers, or PSFCC's that present the opportunity and ability to safely insert and flight test the type of failures and failure protection logic we are currently only able to ground test and simulate. Furthermore, these Production Support Flight Control Computers also have the growth potential for aiding accident investigations by safely inserting and flying failures that are encountered during Hornet operations. One of our recommendations is the continued development of these PSFCC's towards that end.

"It is ONLY software,,,"

- Or, "The evil sneak circuit."
  - Importance of Qualitative Pilot Comments
  - Importance of timely data analysis
  - Results of Improperly Sensed Dual AOA Probe Failure:
    - » FCS AOA goes to zero
    - » Left & Right LEF Deflections go to zero
    - » Rudders toe in
  - Uncommanded pitch-up after weight on wheels

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During the course of the flight testing two project pilots said that the aircraft felt "funny" during flared field landings that were conducted for fuel weight, and not as dedicated test points. The perceived anomalies were debriefed, and the contractor was asked to review and analyze the data.

Unfortunately neither pilot had conducted many flared landings in the Hornet, and were unfamiliar with the flared landing handling qualities. However, both pilots were correct in that the aircraft was not behaving normally. And both pilots commented on how the aircraft felt as though it was pitching up during the flared landing, and that positive forward stick inputs were required to arrest the pitch rate, and then also to start the nose to come back down.

Due to other projects and conflicting priorities the contractor engineer did not analyze the data until much later. Then he reported that there was a longitudinal pitch-up occurring due to the flared landings. The flared landing had both touched down above 10 degrees AOA, all normal landings are conducted at 8.1 degrees AOA, with certain emergency procedures calling for landings above 10 degrees AOA.

The dual AOA probe failure logic was being erroneously triggered by touching down above 10 degrees AOA. This 10 degrees AOA at weight on wheels then via the revised logic toed the rudders in by 30 degrees and drove the leading edge flaps from 17 degrees of droop to 0 degrees. These then were causing the significant pitch-up at weight on wheels.

Improperly Sensed Dual AOA Probe Failure

- Further analysis
  - Trailing Edge Flaps Off Emergency Procedures
  - Lateral Asymmetries
  - Cross Winds and Gusts
- Current Flight Manual Limits
  - Not Achievable for these items

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Further analysis of the flight manual procedures for trailing edge flap failures such as a trailing edge flap actuator failed would result in the trailing edge flaps being inoperative or "off." For such failures the flight manual procedures direct the approach and landing be conducted at 10-11 degrees AOA to reduce the approach speed. Thereby triggering the dual AOA probe failure logic at weight on wheels.

Further simulation conducted with trailing edge flap failures, and any landings with HUD AOA above 10 degrees, especially with lateral asymmetries, cross winds and gusts revealed that departure and roll over during landing roll out could result. The test team cited these deficiencies as unsatisfactory and recommended that they be correct prior to further flight test.

Accordingly, representatives from the Pax River test team met with and briefed the Program Manager and his team at NAVAIR.

Prior to the briefing to the Hornet Program Manager, key meetings were conducted by the program personnel, the testers and the contractors. It was during this unique give and take, exchange of information and ideas and brainstorming that an effective gameplan was quickly drafted. The resulting options were drafted and presented to the Hornet Program Manager in ranked order.

Revised Software:

- Elegant "No-Op'ing" of the Dual AOA Probe Failure Detection Logic
- "Low Risk" addition of a new change to the FCS software
- Smaller Scope
  - Assumption: It is only software - we don't know WHAT could have changed or been affected!!

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The agreed upon solution was to "no-op" the offending dual AOA probe logic and there-by remove the unsafe pitch-up on landing.

The no-op was accomplished by the elegant and effective cutting off of the transmission of the "dual AOA probe failure detected" signal from the rest of the software, flight control system and aircraft. In this fashion, minimal changes were required in the flight controls software, and risk was kept to a minimum.

However, we were not out of the woods yet. A long standing recommendation to incorporate the take-off trim setting of 12 degrees trailing edge up on the stabilators was evaluated as a low risk addition, that was cheaply incorporated. We the testers had a feeling the check was in the mail!

Once again the assumption that it was only software was upon us. We felt that we knew now that any software changes to the flight controls could have effects not anticipated during the decision making or planning stages.

FCS OFP V10.5.1

- Modifications Resulted in a "Good" Tape
- Video of Piloted Simulation
  - Rudder Off
  - Single AOA Probe Failure
  - Flaps Off Landing, with
    - » Asymmetry
    - » Cross Winds

The no-oping of the dual AOA probe failure detection logic resulted in a good, safe upgrade to the flight controls system for the F/A-18 Hornet. Gone were the pitch-up on landing, and false triggering of the logic for aggressive takeoffs.

The twelve degrees takeoff trim change resulted in a certain amount of work and heartache from the required revisions to the flight manual and procedures. The good news was that the change in takeoff trim setting mechanization resulted in no other repercussions or sneak circuit manifestations.

Lastly, a quick video demonstrating the effectiveness of these simple changes.

Conclusions & Recommendations

- Final Flight Controls System Software V10.5.1 is SATISFACTORY.
- Fleet Release of V10.5.1 is Pending

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- Read slide.

Lessons Learned

- Don't Attempt to Squeeze Fail-Operate Performance from a Dual Redundant System (AOA Probes)
- Perform Risk-Benefit Analysis Prior to Implementing "Low Risk, Low Cost Fixes" (Dual AOA Probe Failure)
- Adequate Envelope/Scenario Coverage

- Read slide.

Lessons Learned (continued)

- Dedicated Manpower Support / Priority
- Recommend Continued Development of the PSFCC's to Conduct Inflight Simulation
  - Pitch Oscillations, Visual, Nz & Ny effects
  - Inflight Simulation Yields Results that are closer to the real failure or degrade and physically not available in fixed base simulation.
- Input for Flight Manual (NATOPS) Update

- Read slide.